

An Experimental Study of Boiling in Reduced and Zero Gravity Fields

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A pool boiling apparatus was mounted on a counterweighted platform which could be dropped a distance of nine feet. By varying the size of the counterweight, the effective gravity field on the equipment was adjusted between zero and unity. A study of boiling burnout in water indicated that a variation in the critical heat flux according to the one quarter power of gravity was reasonable. A consideration of the transient burnout process was necessary in order to properly interpret the data. A photographic study of nucleate boiling showed how the velocity of freely rising vapor bubbles decreased as gravity was reduced. The bubble diameters at the time of breakoff from the heated surface were found to vary inversely as gravity to the 1/3.5 power. Motion pictures were taken to illustrate both nucleate and film boiling in the low gravity range.

Introduction

ONE OF THE MOST IMPORTANT environmental changes which man encounters as he leaves the earth is the change in the gravity field. In free space or in an orbiting satellite the gravitational field may closely approach zero. On the surface of the moon or the inner planets of our solar system, the gravitational field is less than that on earth. Heat-transfer processes such as free convection, condensation, and boiling depend on the gravitational body force, and hence will be affected by this new environment. As yet, to the authors' knowledge, there has been no experimental heat-transfer information available for reduced gravity fields. Hence any design calculations for this range must be based upon an extrapolation of theories which have included a gravity parameter, but which have only been checked experimentally at normal gravity. The importance of gravity in the pool boiling mechanism has been demonstrated by the authors in a previous photographic study of boiling in the absence of gravity [1].²

The goal of the present work is to provide quantitative information on how reducing the gravity field affects boiling heat transfer and bubble dynamics. The latter is of some interest in connection with void formation in water-moderated nuclear reactors. Two recent semitheoretical correlations which have been proposed for nucleate boiling are those of Rohsenow and co-workers and of Forster and Zuber [2]. The correlation of Rohsenow takes the velocity of a bubble at the instant of breakoff from the surface as being the most meaningful velocity in the heat-transfer mechanism. Since this velocity depends on the buoyancy force of the bubble, it is not surprising that the heat-transfer coefficient is a function of gravity. However, in the theoretical correlation, gravity appears to only a small power. On the other hand,

Forster and Zuber feel that the radial growth velocity of the bubbles, while they are still close to the surface, is more significant in governing the heat-transfer process. As a result, their heat-transfer correlation is independent of the gravity field. Hence the theories are not in agreement as to the role of gravity in nucleate boiling.

The theories for nucleate boiling do not predict the critical heat flux. An analysis of Zuber [3] on transition boiling gives a prediction of the critical heat flux. The theory is based on a hydrodynamic instability between the liquid and vapor motions near the heated surface. These motions are gravity dependent, and hence gravity appears in the final expressions. A few other theories which are summarized by Cole [4] also predict that the critical heat flux will be a function of gravity. This dependence is investigated experimentally in the present work.

The apparatus used in the present investigation was a modification of that employed in reference [1]. The boiling equipment was placed on a platform which could be hoisted and then dropped a distance of nine feet. A counterweight was attached to the platform to slow its downward acceleration and thereby provide gravity fields between zero and one. A high-speed motion-picture camera was mounted on the platform so that boiling could be photographed for various gravity fields and heat fluxes. The motion pictures in the nucleate boiling regime were analyzed to determine the effect of gravity on bubble sizes and rise rates. Color pictures were taken of film boiling from a red hot surface for a few different low gravity fields. The equipment was instrumented so that a study could be made of the variation of the critical heat flux with gravity field. The critical heat flux data for each experimental run were recorded while the platform was falling through the air. Since the fall lasted only about 1 sec, a proper interpretation of the data required a knowledge of the transients involved in the burnout³ phenomenon. Hence a brief investigation of transient boiling for conditions slightly above the critical heat flux was carried out to provide a better understanding of the experimental results.

³ Since the platinum wire test sections, which were used for this study, failed by melting when the critical heat flux was reached, the terms "critical heat flux" and "burnout" are used interchangeably throughout the paper.

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² Numbers in brackets designate References at end of paper.

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Nomenclature

A = surface area of heated test section
 g = gravity field
 g_n = normal earth gravity field

Q = total heat dissipation from test section
 t_s = surface temperature of test section

t_{sat} = saturation temperature of water
 Δt = temperature difference, $t_s - t_{sat}$

Experimental Equipment

A schematic representation of the apparatus is shown in Fig. 1. This is a modification of the equipment used in reference [1], and hence only a brief description of the basic apparatus will be given here along with a more detailed description of the additions which were made. A cross shaped platform was constructed which was free to move in the vertical direction. A Fastex motion-picture camera, capable of taking up to 5000 frames per sec, was mounted on the platform along with a rectangular tank ($3\frac{1}{2}$ in. \times $5\frac{7}{8}$ in. \times $5\frac{1}{2}$ in. deep) in which the boiling took place. A cable ran from the platform, over pulleys attached to the ceiling, and then down to a counterweight. By changing the size of the counterweight, the downward acceleration of the platform could be varied, and hence experimental runs could be taken at any gravity field in the range between zero and unity. When making a run, the counterweight was pulled down to the floor which raised the platform to the ceiling. The bottom end of the counterweight was grasped by a solenoid operated grapple bolted to the floor. Opening the grapple allowed the platform to fall nine feet before contacting a sand bed which was used as a braking device. For zero gravity conditions, the platform fell freely after being released from a grapple at the ceiling.

Test Sections. An electrically heated element was supported in a brass tank having lucite windows in the front and back faces. The other surfaces of the tank were covered with insulation to help maintain the water uniformly at the saturation temperature. A copper electrode $\frac{1}{2}$ in. in diameter was brought through each end of the tank and supported on the outside by a Teflon flange which insulated it from the tank. Different test sections could be easily clamped to the electrodes. Three types of test sections, which were used for different purposes, will now be described.

The tests to determine the variation of burnout heat flux with gravity were conducted with platinum wires 0.0453 in. in diame-

ter. In reference [5] the boiling curve at high heat fluxes was not influenced when the platinum wire test section was changed from 0.016 to 0.024 in. in diameter. Hence it was hoped that the wires used here would be of sufficiently large diameter so as not to limit the generality of the results. The ends of the wires were soft soldered to copper blocks which were spaced $2\frac{1}{2}$ in. apart. Voltage taps were drilled into the copper blocks as close as possible to the platinum wire so that the voltage drop across the wire could be accurately determined. The copper blocks were then bolted to the two electrodes. Some of the wires were calibrated by the instrumentation section of the laboratory so that they could be used as resistance thermometers and an average wire temperature determined.

The photographic studies to determine bubble sizes and rise rates in the nucleate boiling range, were made using flat nickel ribbons, 0.2 in. wide and 0.010 in. thick. These ribbons were also soldered to copper blocks spaced $2\frac{1}{2}$ in. apart, and then their bottom sides were insulated by cementing them to bakelite strips $\frac{1}{4}$ in. thick. Boiling then occurred from only the top surface, and this provided a relatively simple configuration for making bubble measurements.

For photographic studies of film boiling, the test sections were fabricated from stainless-steel tubing with an outside diameter of 0.157 in. The ends of the tubing were flattened and clamped between copper blocks $2\frac{1}{2}$ in. apart which were bolted to the electrodes. The stainless steel could remain red hot under water for several minutes without burning out.

Power Supply. Power was supplied by a 3-phase Mallory rectifier unit which could provide up to 500 amps dc with about 5 per cent ripple. The power was controlled by a system of Powerstats on the 220 volt a-c line which supplied the rectifier. The d-c current flow was measured by reading the voltage drop across a 0.001 ohm Leeds and Northrup precision resistor placed in series in the circuit. Large loops of flexible woven welding cable, which could fall freely with the platform, were used to carry the current to the electrodes in the boiling container.

Instrumentation. The voltage across the calibrated resistor and the voltage across the heated test section were both measured with a Rubicon potentiometer and light beam galvanometer. The current in the circuit could be determined within ± 0.2 amp at 100 amp and the voltage across the test section read within 0.002 volt at 1 volt. Although this instrument was quite sensitive, there were slight current and voltage fluctuations during the boiling process, and hence the heat dissipation could be in error a few per cent. The potentiometer readings were taken just before the equipment was dropped. To read the transient current and voltage while the equipment was descending, a dual beam oscilloscope (Tektronix Type 535) was used. The bias settings on the two preamplifiers were made to center the initial voltage and current signals, and the gains were set as high as possible so that small changes from the initial values could be observed. Transient temperature changes of the test section were evident if they exceeded about 6 deg F. While the apparatus fell, the signals made a single sweep at 5 cm/sec and were recorded with a Polaroid camera. The 5 per cent ripple from the power supply caused a corresponding ripple in the oscilloscope signals, and this had to be filtered out since it was of the same order of magnitude as the changes to be observed. This was done with a low band pass filter which reduced a 60 cps signal by a factor of 20, but allowed a signal with a frequency of less than 12 cps to pass unaffected. For a step function pulse, the filter gave a full response within $1/20$ th of a second, and hence would adequately follow the signals to be observed. To eliminate spurious signals, the wires in the circuitry were carefully shielded.

The temperature of the boiling water was measured with two copper-constantan thermocouples immersed in the tank and read with a Rubicon potentiometer.

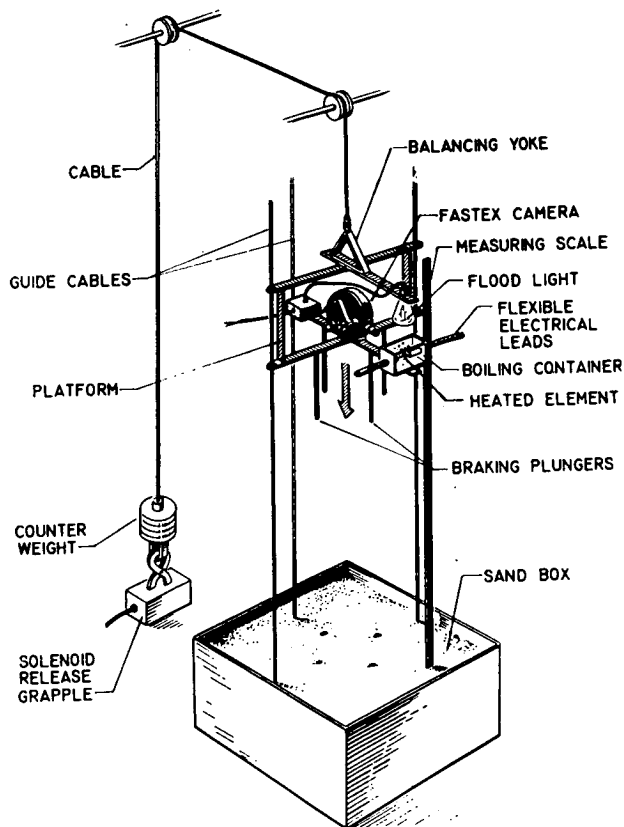


Fig. 1 Schematic diagram of the counterweighted platform

Experimental Procedure

Due to the dependence of the boiling process on many parameters, a great deal of care had to be taken to try to keep conditions the same during successive experimental runs. A learning period of several weeks was necessary before a good experimental technique was achieved. In order to provide a basis for critical evaluation of the work, and to aid any future workers who may use this type of apparatus, a detailed description of a typical burnout test will follow.

Several platinum test sections were fabricated in an identical way, and one was attached between the electrodes in the boiling container. The tank was then filled with boiled distilled water and a 350-w stainless-steel jacketed immersion heater was inserted to bring the water to the saturation temperature. During this time the d-c power was turned on and a moderate current passed through the platinum wire. When the saturation temperature was reached, as indicated by the thermocouples as well as by normal boiling conditions, the immersion heater was removed and the burnout heat flux of the wire was checked. This was accomplished by slowly raising the power in the circuit while watching an ammeter connected into the output of the d-c power supply. At the onset of burnout the increase in temperature of the heated wire caused an increase in resistance in the circuit and hence a decrease in current. As soon as a reduction in current began, the power was immediately shut off. It was found that sometimes the wire could boil normally for a few minutes at a given power setting and then suddenly burn out, and hence the power was raised slowly to provide ample time for the boiling to adjust properly. The transients involved in initiating burnout will be discussed in a later section.

In the instant that the wire started to burn out before the power was shut off, the wire would usually begin to glow slightly in one local region, but no physical damage could be observed. However, when the power was restored, and boiling resumed, it was noted that the region which had started to burn out was deficient in nucleation centers, possibly due to the high temperature which had been reached at that location. This phenomenon has been observed before by McAdams, et al. [5]. If the heat flux was immediately brought up again, the burnout flux was much lower, apparently due to the lack of efficient boiling over part of the wire surface. However, if a period of 2 to 5 minutes was allowed, then the nucleation centers would be restored, and the burnout flux would return close to its former value.

After the burnout check, several minutes were allowed for the nucleation centers to become re-established. Then the power was set at the desired value for the low gravity test, and a counterweight corresponding to the required gravity field was placed at the end of the hoisting cable. The platform was then raised to the ceiling and the cable secured by the solenoid grapple. Potentiometer readings of the voltage and current in the test section were recorded, and the thermocouple readings for the water temperature were taken. Upon depressing a switch the following sequence of events took place. The oscilloscope was triggered and began a two-second sweep. The high-speed motion-picture camera was started to record the initial boiling state before the platform fell. From 0.3 to 0.5 sec later, according to the setting on a timer, the solenoid grapple opened and the platform began to fall. As soon as the drop was complete the power was cut off to prevent the test section from melting in the event that burnout had been initiated while the low gravity environment existed. The existence of burnout during the drop was shown by oscillograph traces of the current and voltage. These showed an increase in voltage drop across the heated wire and a decrease in the current flow due to the increase in wire resistance as the temperature increased. Fig. 2 shows a typical record of the transient current and voltage when burnout occurred. Depend-

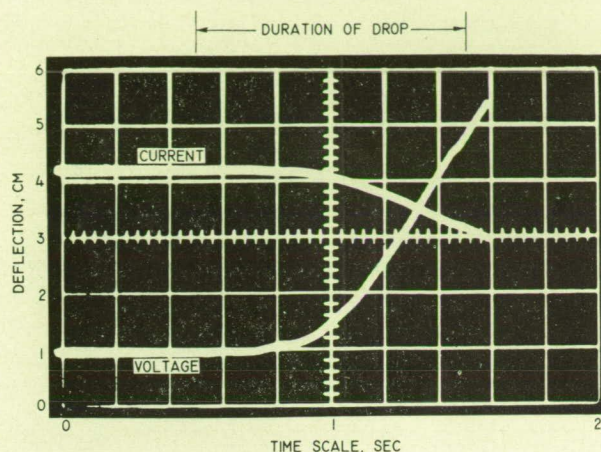


Fig. 2 Behavior of voltage and current in a typical drop test with burnout occurring. (Deflection scales: 0.072 cm/amp, 8.5 cm/volt.)

ing on whether burnout did or did not occur during the drop, the power was decreased or increased by about 5 per cent and another run taken. This procedure was continued until two runs were obtained, one where burnout occurred, and one at a power about 5 per cent lower where burnout did not occur. After these two runs were achieved, the burnout heat flux was checked again at normal gravity for comparison purposes. This procedure was repeated for several different gravity fields and with several platinum wire test sections.

The effective gravity field for a given counterweight size was determined by measuring the rate of descent of the platform. This was accomplished by placing a stationary vertical measuring scale in the viewing field of the falling motion-picture camera to provide a continuous record of platform height on the film. In addition, an argon timing lamp in the camera placed a mark on the film every 1/120th of a second. From the data of distance and time, the acceleration of the platform could be determined.

Effect of Gravity on Burnout

For each series of drop tests at a particular gravity, a heat flow per unit area just above and below the apparent burnout point was computed from the current and voltage measurements. These values were then divided by the burnout flux at normal gravity for that particular test section. The effect of gravity on the burnout heat flux is shown by the data in Fig. 3. It is seen that there is a considerable scatter in the data at each gravity. This is believed to be due to the transients involved in the burnout process, and some experimental results to explain this will be discussed in the next section. In spite of the scatter, the data do indicate a definite trend. For example, at 5.5 per cent gravity the burnout flux has been reduced to about 65 per cent of the value at normal gravity. At 47.5 per cent gravity the wire would not burn out during the drop even for heat fluxes within 7 per cent of the normal gravity burnout limit. Also shown on the curve is a line of $(g/g_n)^{1/4}$ variation. This variation for the critical heat flux has been predicted by a number of investigators as discussed, for example, in reference [4]. The curve appears to provide a reasonable lower limit for the data. The results for zero gravity will be considered in more detail in connection with the discussion in the next section.

Transient Burnout Studies

The data in these experiments were obtained during a time interval on the order of a second while the heated surface was being subjected to a decreased gravity field. The question then

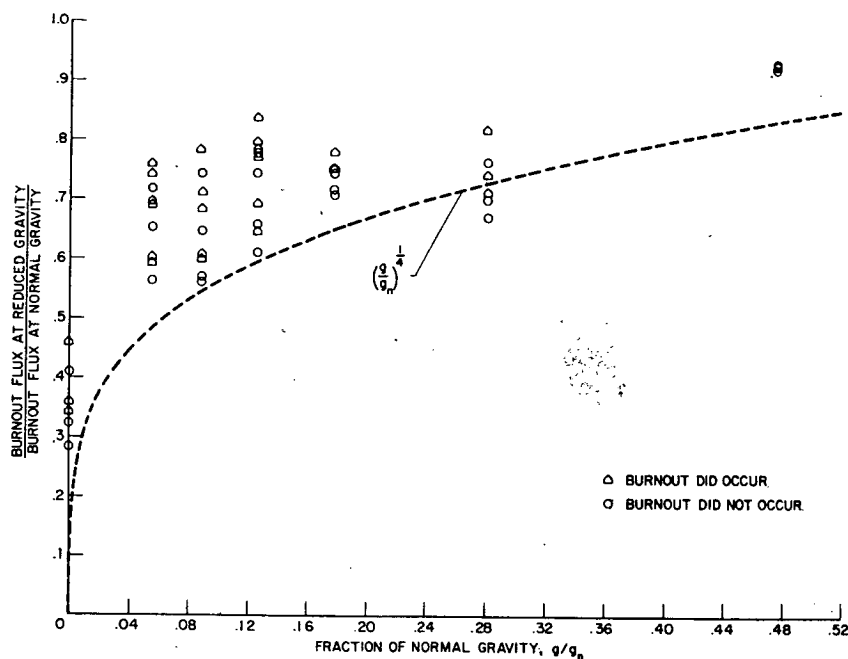


Fig. 3 Effect of reduced gravity on burnout heat flux

arises as to how rapidly the system will respond and indicate a burnout condition after a sudden change in gravity field. For example, if the power were set at the burnout flux corresponding to a certain low gravity, and then the test section were subjected to that gravity, how long would it take for a burnout condition to be indicated? It was necessary to investigate this transient response in order to properly interpret the burnout data.

For this investigation a resistor and a switch were placed in parallel across the heated wire. When the switch was closed, part of the current would go through the resistor. When the switch was opened, the wire received a step increase in power. Using the same instrumentation as in the drop tests, the experiments were carried out as follows: First, the power was slowly raised to determine the burnout flux for the test section. Then the switch on the parallel resistor was closed, and the total current flow was increased so that when the switch was opened the heat flux in the test section would be a certain percentage above the burnout value. Just before the switch was opened, the oscilloscope was triggered on a ten-second sweep to record the current flow and voltage drop across the test wire. From a photograph of the traces, the time from the step in power to the onset of burnout could be measured.

In order to obtain good statistical data on the transient time required for burnout, a large number of tests are necessary. The same test section should be repeatedly subjected to the same power pulse until a good distribution curve is obtained which gives the probability for burnout to occur within a given time. The manual power shutoff which was used to prevent destruction of the test wire was a limitation in this experiment, since it was not rapid enough to prevent the wire from glowing slightly red for each test. After a dozen or so tests this would cause changes in the wire, and the burnout limit would decrease so that the data would become inconsistent. Despite this limitation we can say that for a step in power to 10 per cent above the burnout flux, only about 30 per cent of the burnouts occurred in less than one second. The remaining 70 per cent took from 1 to 5 sec. However, when the power was pulsed to about 25 per cent above burnout, all of the burnouts took place within a second and many of them were essentially instantaneous.

These transient tests could only be performed under normal gravity conditions. However, it is reasonable to assume they apply qualitatively for reduced gravity. The results of these tests offer a possible explanation for the scatter which was observed in Fig. 3. Let us say that a series of drop tests were being made in which the power was increased in increments until burnout occurred. When the power was just above the burnout flux for the gravity field under consideration, there was a fairly small probability that burnout would occur during the short duration of the test, and hence a burnout would only be observed at this power setting in some instances. Most likely the power would have been increased and another test performed. Hence burnout would finally be observed at some higher value where there was a greater probability of the instability taking place within one second. As a consequence, the burnout data would generally be too high, but not by over 25 per cent since at this excess power, burnout within one second would be expected. The very lowest data points at a given gravity would be near the true burnout limit and would be the result of a highly improbable event occurring.

Although there is no experimental evidence on local surface temperature fluctuations in boiling (reference [2]) there is a possibility that these would account for the randomness in the transient burnout behavior. When part of the wire reaches a certain critical temperature the process becomes unstable and burnout occurs. As the mean temperature level of the wire is raised, the probability is increased that locally the burnout temperature could be exceeded in a given time interval. For a power setting which would cause the average temperature of the entire wire to be above the critical value, burnout would occur almost instantaneously.

The transient considerations are especially important for the zero gravity case. In this instance, the theories for the critical heat flux indicate that the burnout flux would go to zero. This, of course, neglects the heat removal that would actually occur by radiation and conduction when the heated surface is completely surrounded by vapor. If the liquid is at the saturation temperature, the vapor cavity may keep increasing in size as time proceeds. For a proper evaluation it would be desirable to have experimental information for periods of zero gravity which are longer than those in the present investigation.

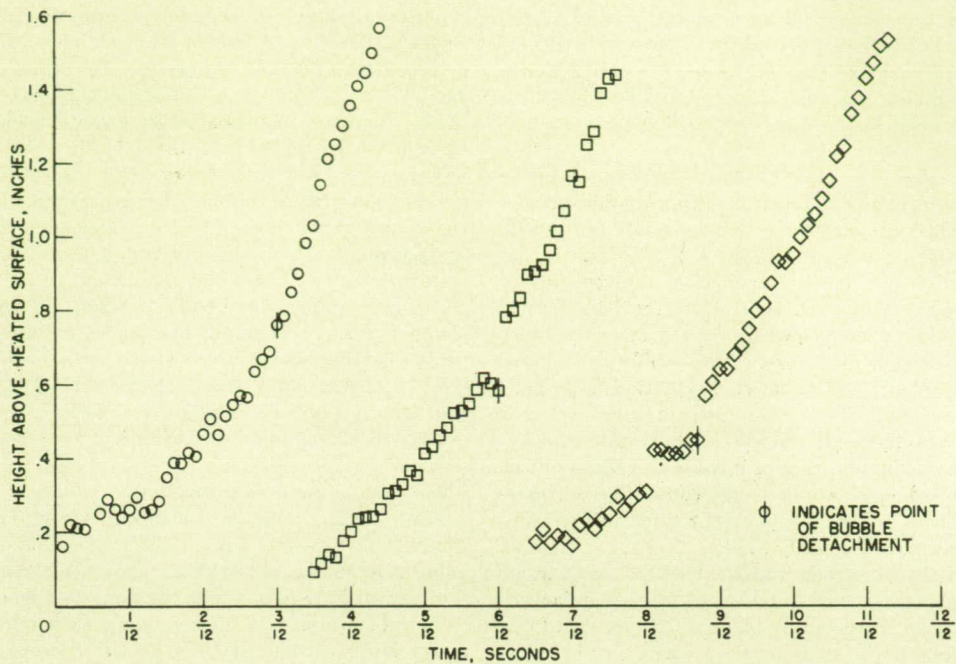


Fig. 4(a) The rise of individual bubbles in 5.5 per cent of normal gravity

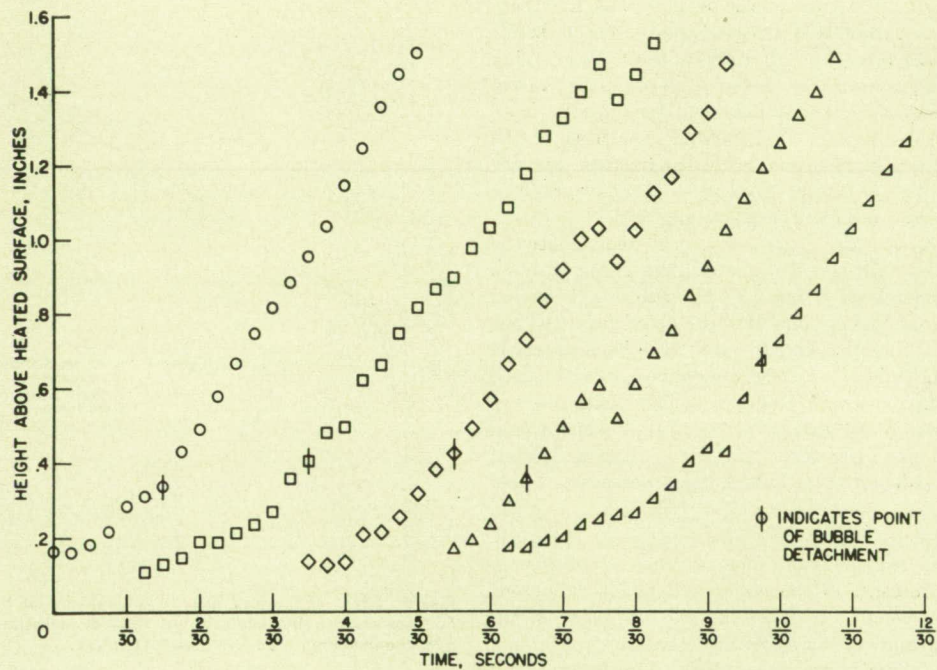


Fig. 4(b) The rise of individual bubbles in 28.2 per cent of normal gravity

Nucleate Boiling at Low Gravity

Photographic Study. A photographic study was made at several gravity fields of boiling from a flat horizontal nickel ribbon with boiling from only the upper surface. The ribbon heat fluxes for the films were all within a few per cent of 91,000 Btu/(hr)(ft²). The motion pictures were placed in a viewer and measurements were taken on about 15 different bubbles for each gravity field. The number of bubbles measured was limited by the low gravity runs where relatively few bubbles are formed because vapor removal is so poor. As soon as a bubble could be distinguished on the ribbon, measurements were taken every 1/120th of a second of

the height of its center of gravity above the ribbon. These measurements were taken until the bubble had traveled about 1.5 in. upward from the heated surface. The center of gravity was estimated at the center of the area of the bubble when it was attached, and at the intersection of the major and minor axes when the bubble was detached. The values of the major and minor diameters were recorded at about six successive 1/120 second time increments immediately following breakoff from the surface.

It was found that in the low gravity range, the bubbles would become quite irregular and poorly defined while attached to the surface. This was due to the poor removal of vapor which would

cause small bubbles to coalesce and form a larger film of vapor. For this reason, the bubbles attached to the surface were very irregular, and hence an average bubble size for attached bubbles could not be determined. Shortly after the bubbles detached, they became much more distinct, and hence diameter measurements could be made for the detached condition.

Bubble Rise Rates. Figs. 4(a) and (b) show typical curves of the heights of the bubble centers as a function of time for 5.5 and 28.2 per cent gravity fields. Although the bubbles had a fairly wide variation in diameters, it is seen that the rise rates for the detached bubbles are all very much the same for a given gravity field. This is in agreement with the results for high bubble Reynolds numbers in reference [6] where the rise rate of bubbles was found to be independent of size. The bubble paths have some irregularities probably due to the stirring action of the boiling process. The resulting convection currents have increased importance at low gravity fields where the buoyancy forces become small. When looking at the films it was noted that bubbles would move downward at times due to the convection currents.

Plots similar to those in Fig. 4 were prepared for each gravity field including the normal one gravity condition. For each bubble path two straight lines were then drawn. One line went in an average way through all the points after the bubble had detached, and hence its slope gave an average bubble velocity for about one in. of rise away from the heated surface. The other line was drawn tangent to curve of the data at the point of detachment, and the slope of this line gave the bubble velocity at the time of breakoff from the surface. An arithmetic average of each of these two rise rates was then computed using all the bubble paths for each gravity field, and these were divided by the corresponding rise rates for normal gravity. Fig. 5 shows the rise rates relative to those for normal gravity, as a function of the gravity field. For normal gravity the average of the bubble velocities at the time of detachment was 0.98 ft/sec, while the average velocity over one in. of rise was 1.17 ft/sec. Except for very low gravities the data points in Fig. 5 fall close to a straight line.

The magnitude of the rise rates and their dependence on gravity did not agree with those of gas bubbles rising through liquids as given in references [6 and 7]. The rise rate measured for normal gravity was higher than that predicted from the gas bubble correlations. Even larger rise rates have been observed in reference [4]. The bubble velocities may have been influenced by cellular convective motions in the tank, which would produce an upward circulation in the vicinity of the heated element, and a downward motion along the sides. In view of these motions it is not known if the calculation of bubble drag coefficients would be very meaningful.

Bubble Diameters. Since most of the bubbles were not spherical, an assumption had to be made to obtain an average bubble diameter from the measurements of the major and minor diameters. Since the third dimension of each bubble into the plane of the photograph was not known, it was decided that any refinement beyond a simple arithmetic average bubble diameter was not warranted. For each bubble, the diameter at detachment was taken as the arithmetic average of several readings taken at successive 1/120 sec intervals immediately following detachment. Then an average was taken of all the bubbles for a given gravity field.

For comparison, information on bubble diameters for the normal gravity condition was needed. This was obtained by starting the motion-picture camera about one quarter of a second before the platform was released. The bubble rise rates for normal gravity did not vary appreciably from run to run, but the bubble diameters could vary by several per cent. This variation in bubble size was possibly due to small differences in water temperature for different runs. Hence the data on bubble diameter for each gravity field was compared with the normal gravity

condition observed immediately before the drop. Fig. 6 shows a plot of the ratio of bubble diameter to normal gravity bubble diameter, as a function of gravity. For normal gravity the average bubble diameter for all runs was 0.245 in. As expected, the bubble diameter increases as the gravity field is reduced. The slope of the line on the logarithmic plot is about 1/3.5. This does not agree very well with theory which indicates (see reference [3] for example) that, for bubbles departing from a horizontal surface, the diameters increase as $1/\sqrt{g}$. This assumes that the bubble contact angle, which also appears in the theoretical expression, is independent of gravity at the instant of bubble breakoff.

A rough comparison of bubble sizes can be seen in Fig. 7 which shows typical photographs of bubbles for five different gravity fields with the same heat flux at the surface. In the pictures, the bubbles appear fairly evenly spaced (the photograph for 13 per cent gravity is especially good) which indicates that in low gravity fields the bubbles continue to be generated in a regular fashion.

Comments on Nucleate Boiling Data. It was thought that, in the nucleate boiling range, a decrease in the gravity field might be reflected in a poorer heat transfer due to the accumulation of vapor near the heated surface. This would require a higher surface temperature to dissipate the same heat flux. Hence during a drop test the oscilloscope traces might show a higher voltage drop and a lower current flow due to the resistance increase of the platinum wire. However, in drop tests where burnout was not

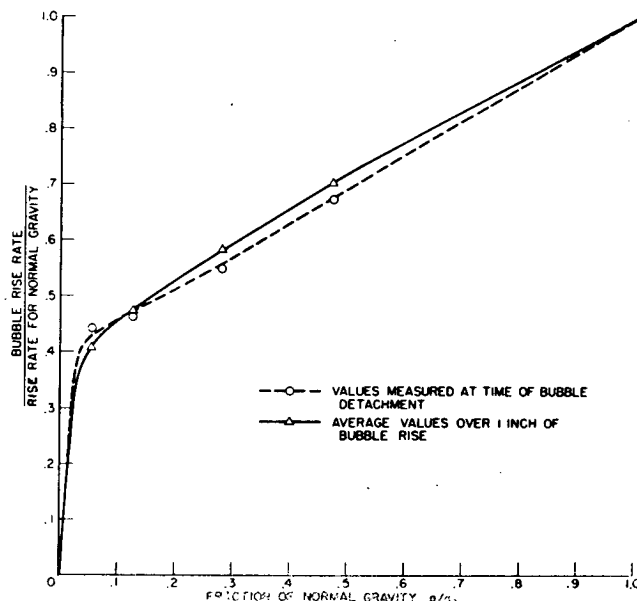


Fig. 5 Effect of reduced gravity on velocity of freely rising bubbles. For normal gravity: Velocity at time of detachment = 0.98 ft/sec, average velocity for 1 in. rise = 1.17 ft/sec.

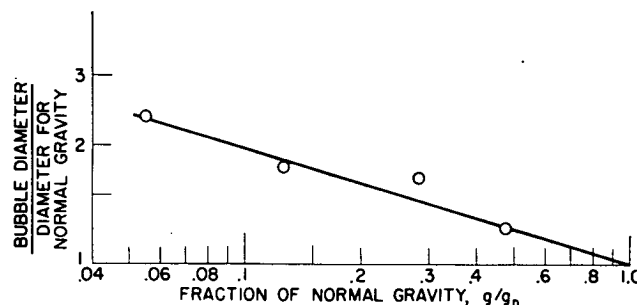


Fig. 6 Effect of reduced gravity on diameter of bubbles at the time of detachment from the surface. Average bubble diameter for normal gravity = 0.245 in.

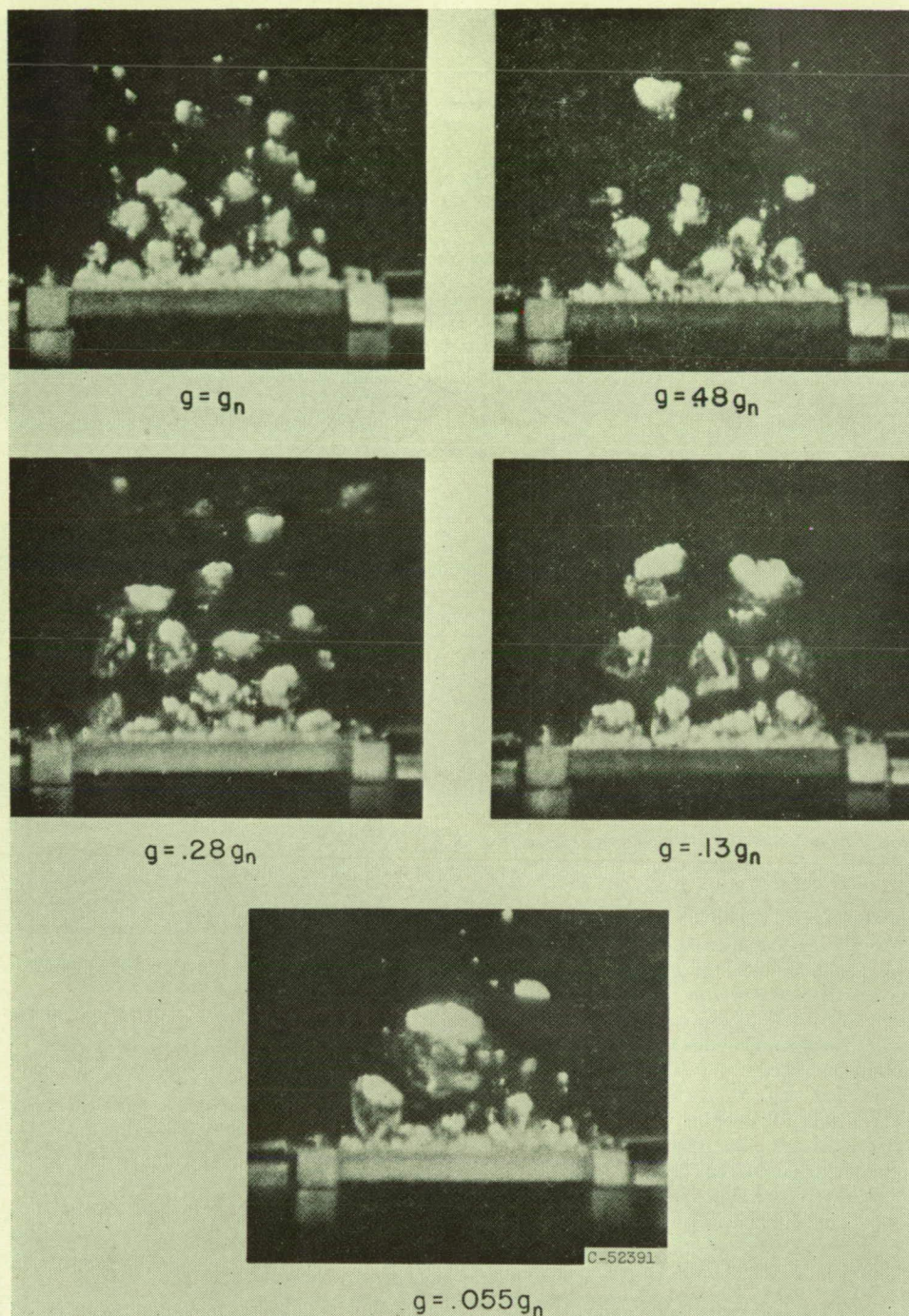


Fig. 7 Nucleate boiling from the top surface of a nickel ribbon for five different gravity fields
Heat flux = 91,000 Btu/hr-ft², g_n earth gravity

present, the traces went straight across the screen and no surface temperature change could be detected. It should be noted, however, that a change could only be clearly detected if it were at least 6 deg F, so that a shift in the boiling curve of Q/A as a function of $t_s - t_{sat}$ could have taken place of less than this magnitude. These results can be justified in terms of the analysis of Forster and Zuber (see reference [2]) which yields a heat-transfer coefficient independent of gravity. Their analysis shows that the "stirring action" of the bubbles, as indicated by the product of the bubble radius and the change in radius with time, is independent of the size of the bubbles. Hence the large bubbles ob-

tained in low gravity fields may be just as effective in promoting good heat transfer. The results of Rohsenow [2] do contain a gravity parameter, but it is to a small power. If Q/A is constant, then Δt is proportional to $(g_n/g)^{1/6}$. For example, if a drop test is performed where g is reduced suddenly to 20 per cent of normal gravity, then Δt would be increased by about 30 per cent. Since the Δt for these tests is on the order of 25 deg F, a 30 per cent change would just be detectable. Hence with our instrumentation, a shift in the boiling curve would only be detected for gravities less than about 1/5 of normal. In this range we still did not observe any change in wire temperature during the experiments.

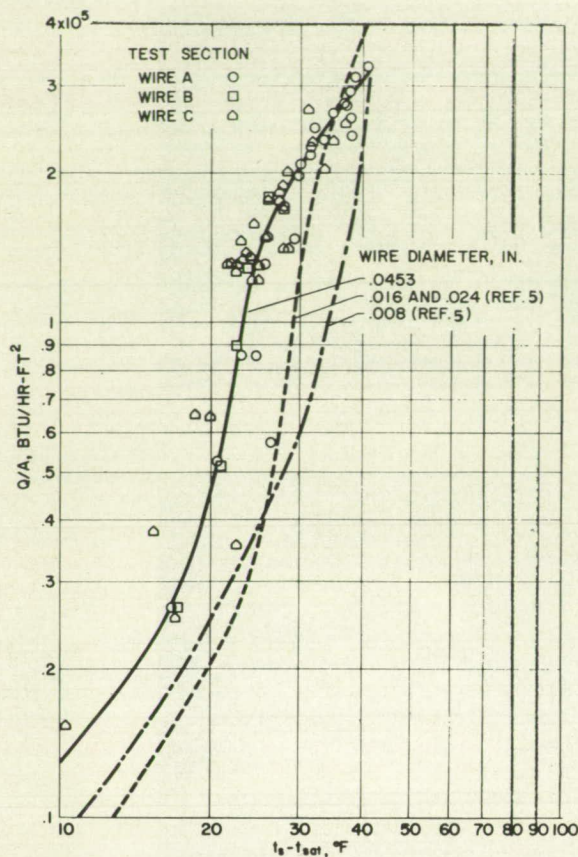


Fig. 8 Nucleate boiling from a horizontal platinum wire in water at atmospheric pressure

The possible shift of the boiling curve to a higher Δt is unimportant with regard to failure of a heating element by melting, except at very low gravities where a continuous vapor film may be formed. At zero gravity the limitation of the short duration of the test is significant, since under these conditions the surface would eventually tend to become surrounded by vapor.

The experimental data recorded prior to each drop test provide information on normal one gravity nucleate boiling. A boiling curve using these data is presented in Fig. 8. The data were taken using three calibrated platinum wires with diameters of 0.0453 in. The resistance measurement of the wire provides an average wire temperature, and a correction for the radial temperature variation was applied as given in reference [5] to yield the surface temperature. There was also an axial temperature variation due to heat conduction from the heated wire to the cooler supporting electrodes. This effect was checked using the results of Callendar (reference [8], p. 152) and found to be quite small so no correction was needed. The figure also shows how the data are located relative to those for smaller diameter wires given in reference [5]. Near the critical heat flux, the data fall in the same range as those for smaller wires. Hence it is felt that the influence of wire diameter is probably unimportant for the burnout data given here.

Motion-Picture Film

A 16-mm narrated color film has been prepared and is available on loan from the NASA, Lewis Research Center. The number of the film is C208 and it is entitled "Boiling in Reduced Gravity," by C. M. Usiskin and R. Siegel. The film shows the experimental equipment and illustrates its operation. Nucleate boiling of water from a horizontal platinum wire is shown for three gravity

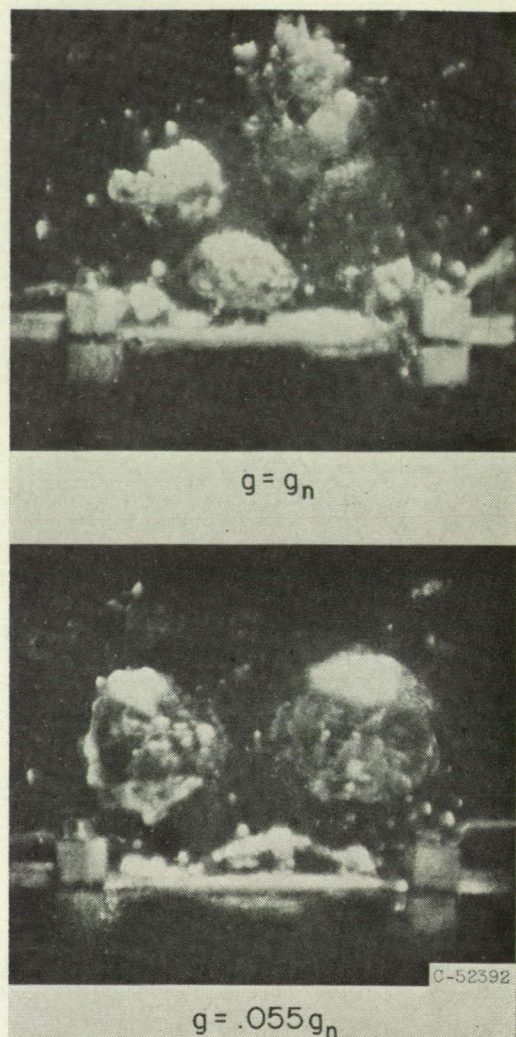


Fig. 9 Film boiling from the outside of a stainless-steel tube for two gravity fields

Heat flux = 127,000 Btu/hr-ft², g_n earth gravity

fields, 28, 5.5, and 0 per cent of normal gravity, and is compared with normal boiling. The heat flux for these three sequences is 230,000 Btu/(hr)(ft²). Then film boiling is shown from the outside of a horizontal, red-hot stainless-steel tube at 5.5 and 0 per cent of normal gravity. The heat flux for these two sequences is 175,000 Btu/(hr)(ft²). The nature of low gravity film boiling is illustrated in Fig. 9. At 5.5 per cent gravity the photograph shows two bubbles which have broken off at each end of the vapor film surrounding the heated tube. A new bubble is growing in the central section between the locations from which the previous bubbles have departed. The formation of bubbles at alternately spaced locations is a well-known characteristic of film boiling and evidently persists for low gravity fields.

Conclusions

The burnout heat flux decreases with decreased gravity as expected from the trend predicted by theory. The theoretical curve which gives the burnout flux varying as gravity to the one quarter power appears to be a reasonable lower limit for the data. If the heat flux is suddenly raised above the burnout limit an interval of time is required before burnout actually occurs. This transient time decreases as the magnitude of the step in power is increased beyond the burnout limit. Because the data in this work were all obtained during drop tests which only lasted

about a second, the transient phenomenon is significant in accounting for the scatter of the burnout data.

The photographic study of nucleate boiling indicates how the velocity of freely rising bubbles decreases as gravity is reduced. The bubble diameters increase as gravity is decreased approximately as gravity to the 1/3.5 power. At zero gravity, film and nucleate boiling take on a similar appearance.

For nucleate boiling, within the limitations of the present experimental equipment, the surface temperature of the test section for a fixed heat dissipation was not influenced by the reduction in gravity field.

Acknowledgment

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DISCUSSION

Marvin Adelberg⁴ and Kurt Forster⁵

We are fortunate to have, in the present paper, one of very few experimental investigations on the influence of gravity upon heat transfer to a boiling liquid. The authors feel that their results, which showed no significant influence of gravity, substantiated the correlations of Forster and co-workers as contrasted with the correlations of Rohsenow and co-workers. We wish to note, however, that the fact that g does not appear *explicitly* in the correlations of Forster and co-workers does not imply that this correlation is independent of g . The correlation constant C in that correlation was obtained by reference to experiments performed under normal gravity ($g/g_n = 1$); for example, had C for the correlation been determined by reference to experiments performed on the moon ($g/g_n = 1/6$), then the influence of g would have been manifested in a new value of C .

To elaborate on this point, by reasoning from dimensional analysis: Assuming four primary dimensions (time, temperature, mass, and length) and noting the large number of significant and

independent variables which appear in the various correlations, it is evident that more than three Π terms are required for a complete set. Thus the additional Π terms which do not appear explicitly are incorporated in the constant C . Should g be a significant independent variable, then at least one of these additional Π terms in C contain g .

We want to take this opportunity to present some physical considerations concerning the relative importance of gravity in the transfer of heat from a heated surface to a boiling liquid. The main function of gravity in this process is the removal of the vapor bubbles from the heated surface. Apart from gravity, the vapor bubbles can be removed from the surface also by forced convection (shear) forces and/or by the flow field induced by the dynamics of the growing bubble. Let us estimate the dynamic force F_d associated with the growing bubble and compare it with the buoyancy force F_b in order to obtain a criterion for the relative importance of the latter. Consider a hemispherical cavity of radius $R(t)$ growing on a flat surface in a liquid of density ρ ; its apparent mass is of the order $2/3 \rho R^3 \pi$, and its velocity is of the order \dot{R} . We set the dynamic force F_d associated with this mass flow proportional to the momentum change

$$F_d \propto \frac{d}{dt} \left(\frac{2}{3} \rho \pi R^3 \dot{R} \right) = 2\rho \pi \left(R^2 \ddot{R} + \frac{1}{3} R^3 \ddot{\dot{R}} \right) \quad (1)$$

and we submit that in a system in which the buoyancy force dominates, the ratio F_d/F_b is small and that when this ratio is large, the system will be essentially independent of gravity as far as removal of vapor from the heating surface is concerned. We therefore form this ratio, which is of the nature of a Froude number,

$$\Pi = \frac{2\rho \pi \left(R^2 \ddot{R} + \frac{1}{3} R^3 \ddot{\dot{R}} \right)}{\frac{2}{3} \rho \pi R^3 g} \quad (2)$$

It is well known that, for a bubble growing in either a saturated or a subcooled liquid, \ddot{R} is negative and, inasmuch as the present is a consideration in orders of magnitude, we neglect the second term in equation (2) and we approximate \ddot{R} by the mean value theorem

$$\ddot{R} \approx \frac{R_{\max}}{t_{\max}^2} \quad (3)$$

in terms of the maximum radius R_{\max} and the time t_{\max} at which this maximum radius occurs. Hence

$$\Pi = \frac{3R_{\max}}{gt_{\max}^2} \quad (4)$$

The problem for the designing engineer is to develop a system under normal ($g/g_n = 1$) conditions such that he can predict its performance for other gravity levels. Equation (4) indicates that the important ratio is that of R/t^2 versus g . For saturated boiling at $g/g_n = 1$, significant times for detachment of the vapor bubbles are of the order of 3×10^{-2} seconds and the corresponding maximum radius is about 0.4 cm. For this condition Π , from equation (4), is seen to be about unity. Without resorting to new experiments, we can take advantage of the fact that, for a subcooled liquid, in which the bubbles collapse due to condensation (rather than being detached by gravity), the boiling mechanism should not be significantly influenced by gravity. We might conclude from this that values of Π corresponding to the subcooled case indicate a system which is insensitive to changing conditions of gravity. To obtain a feeling for the magnitude of Π under such

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conditions, we tabulate below some experimental data reported by Ellion⁶ for water:

Table 1 Effect of subcooling upon the ratio Π

Liquid temp T_L -deg F	R_{max} cm $\times 10^{-2}$	t_{max} sec $\times 10^{-3}$	Π [Equation (4)]
[212]	40	30	1.3]
170	5.3	1.1	130
120	4.4	0.83	190
60	3.4	0.50	410

We conclude that a system which is characterized at $g/g_n = 1$ by a value for Π greater than, say, one hundred is essentially insensitive to change of gravity. The relatively very low value of Π in the first row of the foregoing table suggests that a system designed for pool boiling of a saturated liquid at $g/g_n = 1$ will fail at low g levels. This is so for the following reason: In order to produce sizable dynamic forces of the growing vapor bubbles in a saturated liquid, the superheat would have to be extremely high; but superheat is limited to low values by the occurrence of "burnout." Deeper insight into these questions might be obtained by the experiment suggested below.

The authors stress the desirability of experimental investigation of extended duration to minimize transient effects. We would appreciate the authors' comments on some experiments, proposed by one of us a few years ago, intended to yield design criteria for heat-transfer components to operate independently of the level of gravity. Essentially, the designer needs to know two criteria regarding the boiling process, for his system designed under $g/g_n = 1$ conditions, to remain largely unaffected by reduction in gravity: (1) The level of subcooling and/or superheat at which the bubble *dynamic forces* dominate and are sufficient to insure removal of the bubbles from the heating surface. (2) The velocity in forced convection at which the *shear forces* near the heating surface dominate and are sufficient to remove the vapor from the heating surface. A simple experiment which will yield the foregoing design criteria and which permits the observation of the phenomena in the steady state is the following: Consider a system with a flat heating surface on top of and in contact with the liquid. In this case gravity tends to keep the bubbles attached to the heating surface instead of aiding their removal (as takes place in the "heating from below" condition); in this manner one can observe a system in which g/g_n is effectively -1 , and one can obtain experimentally the relation between boiling heat transfer and the usual parameters (superheat, subcooling, convective velocity, and so on). The desired above-mentioned criteria would be established for the range $-1 < g/g_n < +1$ when superheat, subcooling, and convective velocities were found such that the resulting heat flux in this "heating from above" case approximates the heat flux obtained by "heating from below." In this manner, criteria for sufficient conditions for proper heat-transfer design at low gravity can be established conveniently (at rest) by observing the operation at $g/g_n = -1$.

C. P. Costello⁷

This writer wishes to congratulate the authors not only on obtaining significant data but also on presenting the information clearly and completely so as to facilitate appraisal of the data.

The use of a 0.0453 in. diameter wire for burnout studies should give slightly low values of burnout heat flux according to Bernath.⁸ He has accumulated data for nonaccelerating pool boiling

⁶ Max E. Ellion, "A Study of the Mechanism of Boiling Heat Transfer," Jet Propulsion Laboratory Memorandum No. 20-88, California Institute of Technology, March 1, 1954.

⁷ Assistant Professor, Mechanical Engineering, University of Washington, Seattle, Wash. Assoc. Mem. ASME.

⁸ L. Bernath, "A Theory of Local Boiling Burnout and Its Application to Existing Data," AIChE paper 110, presented at ASME-AIChE Heat Transfer Conference, Storrs, Conn., August, 1959.

systems which show that heater diameters up to roughly 0.1 in. are influential in determining burnout. The peak heat flux for a wire of 0.0453 in. diameter appears to be roughly 85 per cent of that obtainable with heaters above 0.1 in. diameter.

The fact that no changes of $t_b - t_{sat}$ with various accelerations were observed is understandable. Costello and Tuthill⁹ observed that acceleration up to 40 times the local acceleration of gravity produced a maximum change of 4.0 deg F in $t_b - t_{sat}$ at a heat flux of 200,000 Btu/hr-sq ft. That is, the increased acceleration lessened rather than improved the heat-transfer coefficient. The writer believes that with accelerations slightly less than the local acceleration of gravity the heat transfer would improve, but so minutely as to be unobserved in the tests reported here.

When acceleration is reduced, bubbles adhere to the heater and remain near the heater longer. In itself, this would add resistance to heat transfer. However, the fact that the bubble can attain larger size and promote more turbulence near the heater apparently more than compensates for this. Thus there should be some optimum acceleration from the standpoint of heat-transfer behavior at which the net improvement of heat-transfer coefficient is maximized. The data of Merte and Clark¹⁰ and Costello and Tuthill seem to indicate that this acceleration will be somewhat less than the local acceleration of gravity although this is a surmise at present.

Analytic predictions of burnout heat flux are based on cases where the acceleration always has the same orientation with respect to the heater surface over the entire surface. In the case of an accelerating cylindrical surface this is not the case; this would seem especially important since varying the orientation of the acceleration would alter its effect on the stability of the boiling system. Stability criterion have been used extensively in deriving burnout heat-flux correlations.

In view of this, it is interesting to note that the burnout data still agree quite well with the analytic predictions. At the University of Washington, burnout data have been obtained for accelerating cylinders with accelerations from 20 to 40 times the local acceleration of gravity. Considerable work remains to reduce these data, but a preliminary reduction indicates that agreement with the analytic prediction that burnout flux is proportional to acceleration to the one-fourth power will be very good. Thus the authors' data and that obtained at Washington for accelerations above the local acceleration of gravity seem to agree with the analytic prediction of the effect of acceleration despite the fact that the analyses have been carried out on much simpler systems.

The writer congratulates the authors on their efforts and feels that this paper will aid materially in the understanding of the burnout phenomenon and the appraisal of various burnout heat flux correlations.

Authors' Closure

The authors would like to thank Dr. Adelberg and Professors Forster and Costello for their interesting discussions which are a valuable supplement to the paper.

With reference to the correlation constant C , we did not detect any shift in the boiling curve of heat dissipation versus temperature difference for the range of conditions that were studied. These conditions were limited to saturated pool boiling with moderate and high heat fluxes. As mentioned by Professor Costello, the change in $t_b - t_{sat}$ was also found to be small when the gravity field was increased to as much as 40g. Further in-

⁹ C. P. Costello and W. E. Tuthill, "Effects of Acceleration on Nucleate Pool Boiling," Presented at AIChE-IMI Meeting, Mexico City, June, 1960. To appear in AIChE Symposium.

¹⁰ H. Merte, Jr., and J. A. Clark, "Pool Boiling in Accelerating Systems," published in this issue, pp. 233-242.

vestigation with more sensitive instrumentation would be desirable in the low gravity range.

From the present study, some rough computations can be made for the dimensionless group $\Pi = 3R_{\max}/gt_{\max}^2$, which is the ratio of the dynamic force to the buoyancy force on a bubble. For R_{\max} the information in Fig. 6 can be used as an approximation. This gives the bubble diameters, for various gravity fields, at the time of detachment from the surface. Since these are the maximum sizes that the bubbles attain at the surface, we shall use one half of these diameters for R_{\max} . Fig. 4 shows the rise of typical bubbles in two gravity fields, and the points of detachment from the surface are given. The authors have additional bubble histories for these gravity fields and for the other gravity fields which were studied in the experiment. We shall define t_{\max} as the time from the origination of a bubble to the instant of detachment. The instant at which a bubble was formed could not be determined due to lack of resolution in the high-speed motion pictures, but a rough approximation can be obtained by trying to extrapolate the curves to zero height. This is very crude but still should give values for t_{\max} which are not in error by more than a factor of about 2, and hence the Π values should be within an order of magnitude. The comparisons between different gravity fields should be better than this since the sets of data were each treated in the same fashion. Average data for various gravity fields are given in the table:

Fractional gravity g/g_n	R_{\max} , in.	t_{\max} , sec	Π $3R_{\max}/gt_{\max}^2$
0.055	0.29	0.32	0.40
0.126	0.22	0.17	0.47
0.282	0.20	0.14	0.28
0.475	0.15	0.067	0.55
1.0	0.12	0.045	0.46

The Π term does not exhibit any definite trend with gravity and remains essentially constant. This results from the large increase in the time scale as g is reduced which offsets the increase in R_{\max}/g . It should be mentioned that the approximation of hemispherical bubbles growing radially may be poor for the boiling regime we investigated. Most of the bubbles that were ob-

served were quite irregular during the period while they were attached to the surface.

The experiment proposed by Adelberg and Forster appears to be a good way to compare the shear forces due to forced flow with the buoyancy force. The results would probably be most meaningful for subcooled boiling since the two-phase flow that would result in saturated boiling for negative gravities might be quite different than for zero and positive gravities. For subcooled boiling, the experiment should yield criteria such as the degree of subcooling necessary for boiling to be independent of gravity. For subcooled pool boiling, the removal of heated liquid from the general neighborhood of the surface may be dependent on a free convection circulation since the stirring action of the bubbles is confined to a region close to the heated surface. The free convection will cease for zero gravity, so a small forced circulation may be necessary to keep the liquid subcooled near the surface. We recently saw some motion pictures taken at Wright Field of slightly subcooled boiling in zero gravity. The immersion heater had a large surface area compared with the size of the bubbles formed on it. The bubbles were propelled off the surface a short distance before condensing, so that the dynamic forces must have been large in this instance. The use of subcooled boiling is, of course, limited to applications where cooling is desired, but a net vapor generation is not required.

Professor Costello mentions the errors brought about by using small-diameter heating wires to determine the burnout heat flux. This situation could be aggravated in low gravity fields since in this instance the bubbles are much larger and hence the comparative scale of the wire size is reduced. Also for a heated wire in reduced gravity the bubbles can easily grow completely around the circumference of the wire, which is in contrast to bubbles spreading sidewise over a large surface. It would be very desirable to have experimental data for bubbles growing on large surfaces in low gravity fields.

It is interesting that the experimental results for burnout in high gravity fields also appear to substantiate the analytical predictions for the gravity dependence. The analytical predictions were made before any data were available for gravity fields other than one g . It is satisfying when the predictions of a simplified analysis are later verified by experimental evidence.